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14. ABSTRACT

Design of polymer composites with specific engineered electromagnetic properties are of use in a variety of physical electromagnetic systems above 100 MHz. In physical electromagnetic systems, e.g., GPS, radomes, WiFi, etc., proper choice of the material can be transformative in that it can yield considerably better performance. Of interest to us is the possible development of low loss magneto-dielectric composites. This project investigates various aspects of material systems, starting with possible composite designs, to design of measurement techniques to development of finite element models for complex waveguide and conformal antenna configurations that use these materials.

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Magneto-dielectric composites, characterization, design of measurement systems, generalized finite element method, complex waveguides, conformal antennas

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RF Polymers II

Final Report

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SUMMARY OF ACCOMPLISHMENTS

RF Polymeric composites offer a whole new design space to radio frequency (RF) engineers. Specifically, the current interest in magneto-dielectric polymer nanocomposites is due to the fact that these materials can have non-trivial permeability and permittivity. Such material properties offer designers the ability to miniaturize certain common passive RF components, such as antennas, radomes, and transmission lines among others. The rationale for using these materials for such a purpose lies in the fact that at a given frequency, the wavelength in the material is smaller than that in air or in a non-magnetic material with identical permittivity. Examples of RF devices for which this is true is the patch antenna where the dimensions of the patch are approximately one half wavelength in the substrate material.

However, several hurdles remain towards the goal of realization of these composites. The most challenging is to realize a significant relative permeability (with a value between 2 and 10) without significant loss at frequencies of interest; in particularly, across a large bandwidth to permit rapid communication rates. It has been shown in several related projects over the past decade that merely crushing the magnetic material and dispersing it in a polymer matrix (a significant challenge in its own right due to the disparity on mass density between typical magnetic inclusions – such as iron, cobalt, ferrous oxides, etc. and the polymer) results in a significant, near total, demagnitization of the resulting composite. Hence, it does not meet the requirement for a non-trivial permeability. Secondly, by grinding the magnetic material into small particles (even, nanometer-class particles), the increased interface can result in enhanced loss at microwave frequencies. Hence, resulting in a material with too high a loss factor.

Hence, the most serious challenges in magneto-dielectric polymer composite realization is one of interface engineering and synthesis methods. Such topics are beyond the scope of this project. Rather, this present project aims to produce guidance for the design and use of such materials based on first-principles electromagnetics. This study has in its self a number of challenges.

The first is the development of methods to design these composites. It has been shown that classical mixing models fail to predict the properties of these composites, and a uniform dispersion of nanospheroids in a dielectric host does not result in the desired properties. Next, it is necessary to develop accurate methods to predict the properties of these materials when used in applications. Finally, it is necessary to develop methods that can accurately simulate applications that use this material. In what follows, we shall briefly summarize our accomplishments in the three areas followed by a list of papers and theses that were published in support of this project.

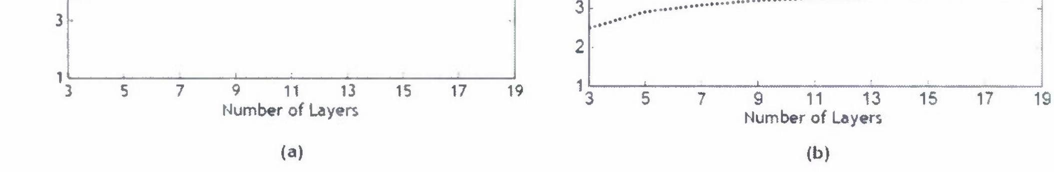
This project has also supported a number of investigators, both at the professional and graduate student level. Significantly, four of the five students partially supported at one time during the execution of this project are either US citizens or US permanent residents. Hence, the project also developed talent in the service of the Air Force mission.

Composite Material Design and Characterization for RF Applications

The design of RF materials depends on various factors such as geometry, volume fraction, thickness, permittivity and permeability of various constituents. Composite design using Maxwell Garnett or Bruggeman formalism is invalid for dense composites as they do not adequately account for mutual coupling. More accurate models are necessary to understand, and thereby, design these composites. In this project, we have undertaken a systematic path to extracting effective properties. We first consider layered composite structures (or 1-D inhomogenieties) and then composites fabricated using rods (2-D inhomogenieties). The analysis of the former can be done using transmission matrices whereas the latter require two-dimensional electromagnetic method of moments scattering codes. In addition, in order to ensure that the structure is infinite in extent, it was assumed to be periodic. This ensures that while the computational domain is bounded, the composite being simulated is infinite. Material properties are extracted using "in-house" algorithms that require the transmission and reflection coefficient.

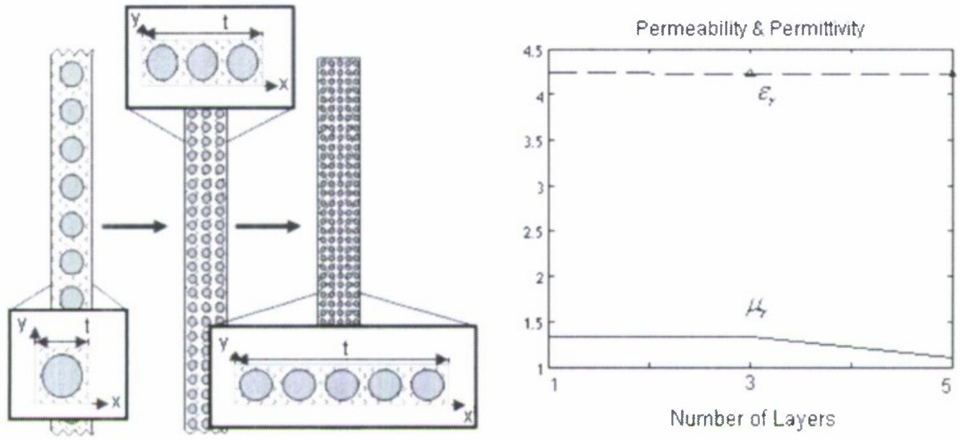
To this end, consider two types of composites: (i) that comprise of a set of layers and (ii) those that comprise of cylindrical rods. For instance, a composite that comprises of alternate layers of Teflon and YIG (yttrium garnet) demonstrates higher values for both the permittivity and permeability as seen in Figure 1.

However, studies on two-dimensional YIG cylinders that are arranged in a periodic lattice show that our enthusiasm has to be tempered. In Figure 2, scattering form a finite slab that comprises of the cylinders of YIG that are repeated in a periodic manner as shown in Figure 2. The permittivity and permeability extracted from the reflection and transmission coefficient show that this structure does not respond as well as in a layered configuration.



(a) (b)

Figure 1: Effective (a) permittivity and (b) permeability for composites comprising of alternate layers of YIG-Teflon-YIG (FDF) or the other way around for different volume fractions of YIG.



(a) (b)

Figure 2: (a) Periodic configuration analyzed; (b) effective relative permittivity and permeability.

These are just snap shots of results for a design scenario. The methods develop permit rapid theoretical design of the composite. In addition to this work, various characterization methods and fixtures are fabricated to determine the effective parameters of these composites. Details of the work done can be found in [1].

Material Characterization of A PEC backed mossy media using a slot waveguide

Typically, it is not always possible to specify in advance the material shape of a sample for evaluation. Many researchers, investigating new materials, are not able to mold the material with tight tolerances. Rather, the sample is provided in a manner consistent with the synthesis procedure. Hence, in addition to developing methods for material design, it is important to develop methods for material characterization. However, the motivation here is to develop and validate non-destructive material characterization techniques for near lossless through lossy, linear, homogeneous and isotropic media, and to be able to extract constitutive parameters when these are backed by a perfect electrically conducting surface. However, in order to extract both the permittivity and permeability of the media, two independent experimental interrogations of the material are required. For a rectangular waveguide the experimental interrogations take the form of either refection or transmission coefficients. The experimental data is then compared iteratively to the formulation, resulting in the extraction of the complex constitutive parameters for the media. Guided by theoretical analysis, we have developed an experimental method to extract material parameters using a transverse slot in a waveguide that rests flush with the material backed by a PEC. A two-dimensional Newton's complex root search algorithm is used to iteratively solve for the complex constitutive parameters. Results for a magnetic radar absorbing material are compared to measurements using a partially-filled rectangular waveguide to validate the formulation. Details on the methodology, as well as several papers (one of which received the best student paper award) can be found in [2].

Generalized finite element methods for analysis of complex waveguides and cavities
Classical finite element methods have become a mainstay in computational electromagnetics [3]. However, the development of magneto-dielectric composites implies that there is a need for methods that are both higher order accurate, highly adaptable in terms of meshes and efficient in terms of the computational time. Furthermore, it would be highly desirable of this methods was sufficiently adaptable to overcome phase dispersion errors in complex wave-guides such as the one shown in Fig 3. Over the years, we have developed a new method, called the Vector Generalized finite element method (GFEM), that permits the use of arbitrary basis functions, does not rely on a mesh, and is highly adaptable [4]. During this period, we have developed methods to incorporate boundary integrals, methods to understand problems associated with dispersion, and have used this method to study propagation in complex cavities and waveguides. As is evident Figures 4-8, the computed results agree very well with measurements and/or comparison computations. These methods are currently being used for obtaining scattering parameters form complex waveguides that contain these polymer composites.

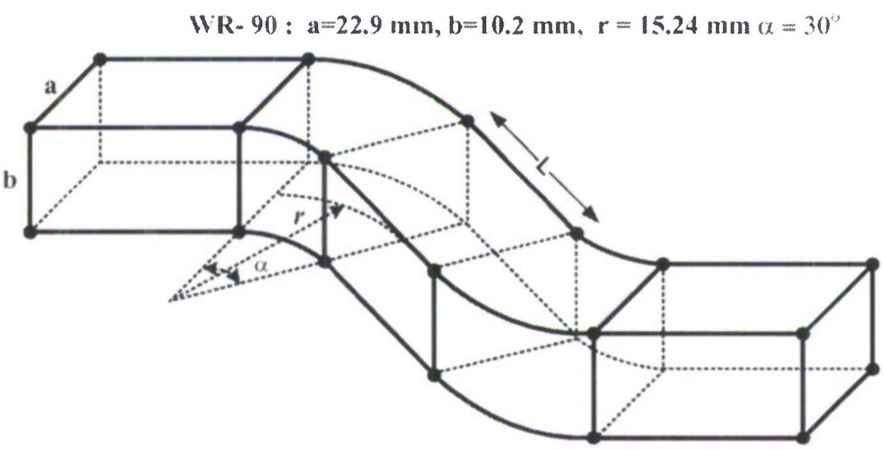
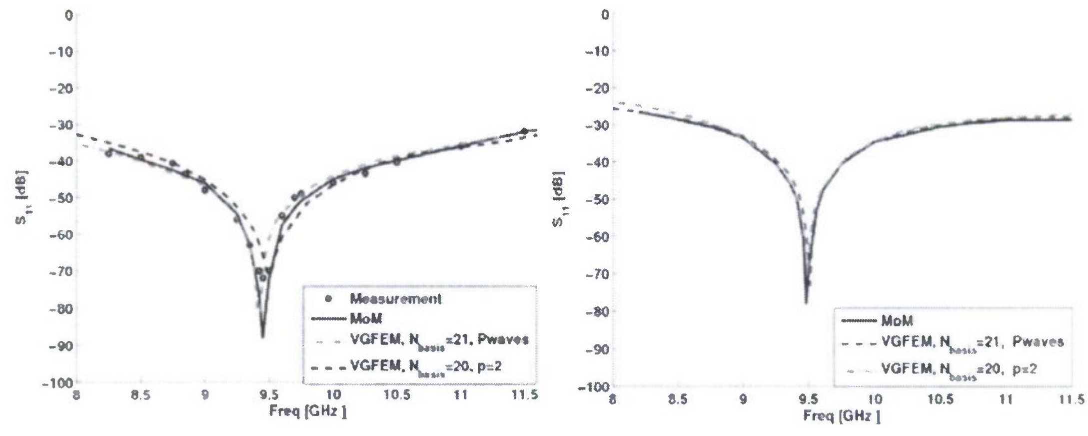
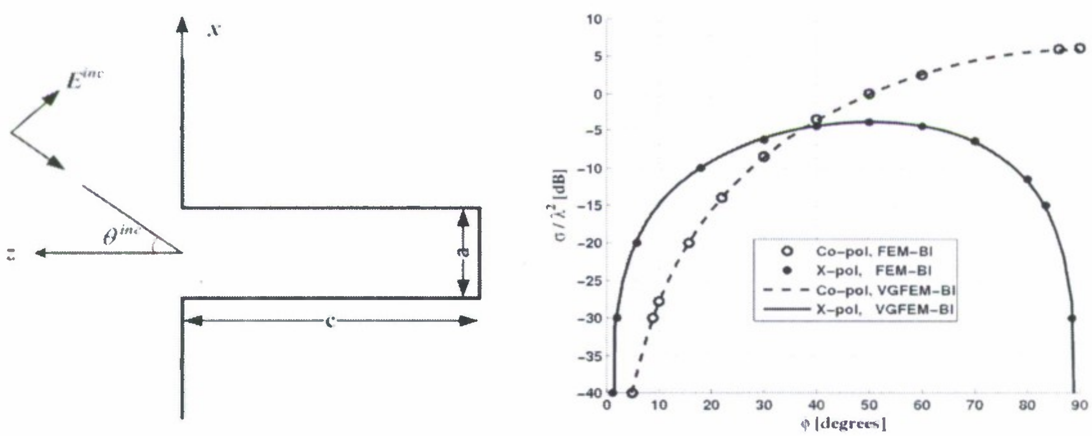


Figure 3. Geometry of WR-90 waveguide with variable segment size of *L*.



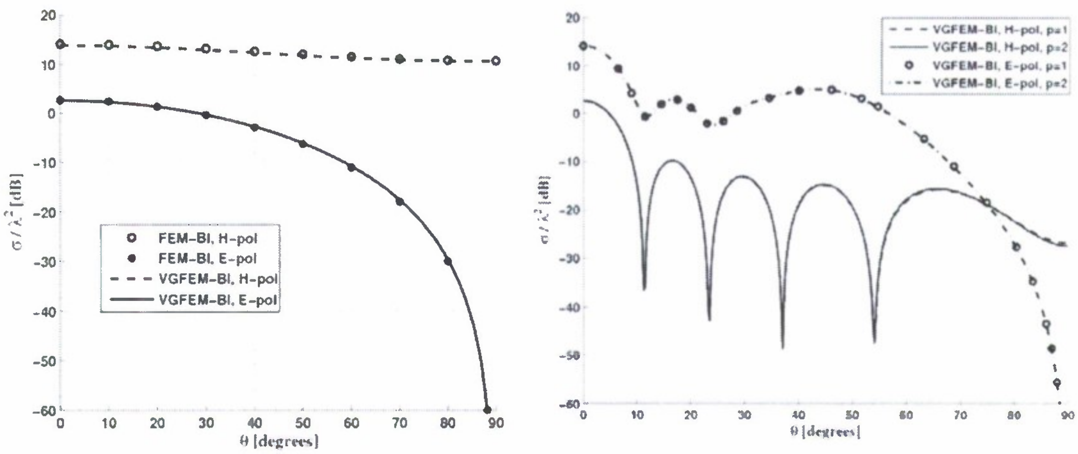
a) L= 0 mm *b) L= 25 mm*

Figure 4. S_{11} of WR-90 waveguide is simulated using different local approximation functions and compared against MoM data [5] for $L=0\ mm$ and $L=25\ mm$.



a) Cavity geometry b) Monostatic radar cross section

Figure 5. Backscattered RCS of a cavity-backed aperture with $a=0.7\lambda$, $b=0.1\lambda$, and $c=1.73\lambda$, is compared against FEM-BI results [6]. A theta polarized field is incident to the cavity with $\theta^{inc}=40°$.



a) $\phi^{inc} = 90^o$ *b)* $\phi^{inc} = 0^o$

Figure 6. Backscattered RCS of a cavity-backed aperture with $a=2.5\lambda$ $b=0.25\lambda$ and $c=0.25\lambda$ is compared against FEM-BI results [7].

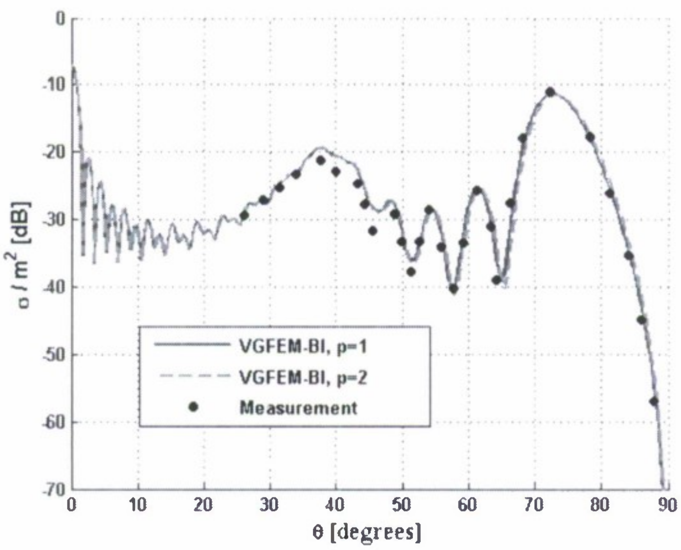
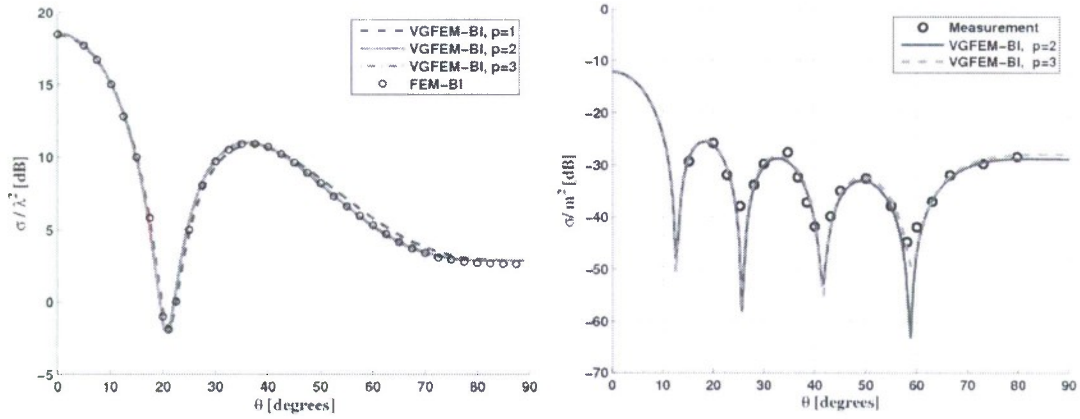


Figure 7. Backscattered RCS of a cavity-backed aperture with $a=16.26\lambda$, $b=0.2\lambda$ and $c=0.85\lambda$ is compared against measurement results [8]. PU domains size of $h_p=\lambda/2$ is used.



a) Empty cavity, 1.5λ x 1.5λ x 0.6λ

b) Filled cavity, *2.89in x 2.1in x 0.057in*

Figure 8. Backscattered RCS's of empty and filled cavities are simulated for theta polarized incident field . RCS of filled cavity with $\varepsilon_r=4$ is compared against measurement [10] at 9.2GHz.

Evaluation of Antenna Performance with Certain Magneto-dielectric Materials

Another aspect of this research project involved the evaluation of synthesized materials as potential antenna-loading material. Michigan State University collaborated with a number of material samples from a number of AFOSR-sponsored colleagues. The primary collaboration provided involved the evaluation of material properties, typically in the frequency range of 10-1000 MHz using an Agilent E-4991A Material Analyzer.

One of the most promising was developed by Prof. John Xiao of the University of Delaware. This material was produced as part of an AFOSR STTR project funded through Spectrum Magnetics. Figure 9 illustrates the measured complex permittivity and permeability of a sample provided by Prof. Xiao.

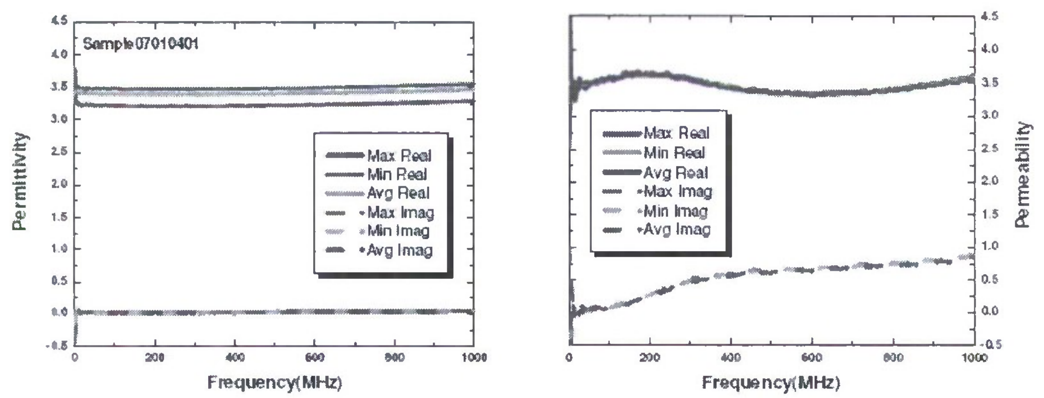


Figure 9. Measured permittivity (left) and permeability (right) of a magneto-dielectric nanocomposite provided by the University of Delaware.

The permittivity is low loss while the permeability has a somewhat larger loss factor. This is seen by the spectral dispersion of the measured data. As a consequence of causality, as represented by Kramers-Kroenig relations, a dispersive material is also dissipative. Nevertheless, this is a promising material since the loss is relatively low and in a spectral band (VHF-UHF) that suggests the potential for a reduction in loss based upon fundamental magnetics principles through more research.

Michigan State University utilized a hybrid finite element-boundary integral method full-wave analysis computer program to evaluate the potential of this material as a substrate for a patch antenna [11]. This geometry was chosen due to the fact that the electromagnetic fields are confined preferentially (though not totally) in the substrate – hence the material properties should have a significant impact on antenna performance properties – and that a paper by Hansen [12] predicted an enhanced bandwidth for a patch antenna printed on a magneto-dielectric as compared with a non-magnetic material. Figure 10 illustrates the voltage standing wave ratio of such an antenna in the VHF band. This antenna is 10cmx10cm printed on a 3mm substrate.

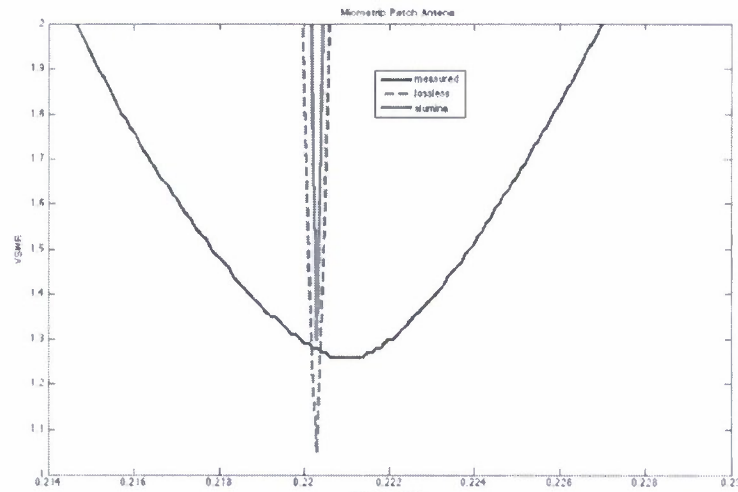


Figure 10. Predicted voltage standing wave ratio results for a VHF microstrip patch antenna printed on the University of Delaware materials (measured data used, see Figure 9), alumina (a common substrate material), and a fictitious lossless version of the UDel material.

This data indicates that the large functional bandwidth of the antenna using the University of Delaware material is primarily due to the loss of the material. The way to think of it is that for a purely resistive transmission line (say 50 Ohms), a pure resistor of 50 Ohms has infinite VSWR bandwidth. However, it is unfortunately not an antenna. In a similar manner, an antenna made with the Delaware material is inefficient. Hence, it may very well be suitable for receive-only applications such as an antenna used for VHR signal intelligence; however, it is not suitable for transceivers such as radars and communications gear. Note that if the material were to be lossless, the bandwidth is greater than that of a non-magnetic material such as alumina as predicted by Hansen [12].

The radiation pattern for the antenna printed on the UDel material is shown in Figure 11.

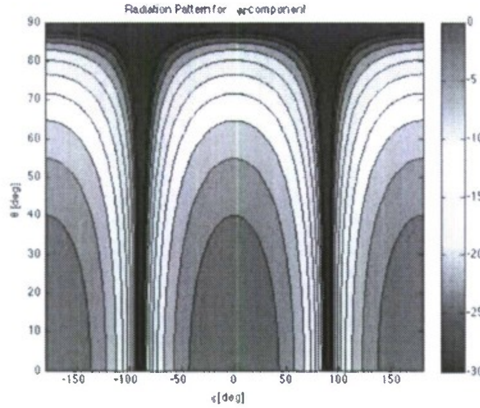


Figure 10. Predicted radiation pattern for a microstrip patch antenna printed on the University of Delaware material at 221 MHz.

In this figure, the radiation peak occurs at broadside (e.g. normal to the face of the antenna) where the elevation angle is 0 degrees. This is a typical pattern for a small patch antenna. Note that the radiation dimension is smaller than a half wavelength in free-space and so the main lobe is a bit broader than the case would be for a half wavelength aperture. Further details on this work are given in [13].

Negative-index Materials Comprising of Plasma Tubes and Ferrimagnetic Materials

Negative-index materials (NIMs) also known as double-negative (DNG) materials have been the subject of a large number of scholarly work over the past decade. Indeed, in collaboration the Air Force Office of Scientific Research and the Army Research Office are sponsoring three (3) Multi-disciplinary University Research Initiatives (MURIs) in this subject.

Michigan State University was interested in assessing the potential for synthesizing such a material using ferrimagnetic materials and plasma tubes. The genisis of this idea is that just above the ferromagnetic resonance (FMR) frequency, the effective real component of the permeability of a ferrimagnetic material is negative (unfortunately, due to the large dispersion in this spectral region, the dissipation attributed to the magnetic property of the material is very large). Deep sub-wavelength arrays of metallic rods have been used to sunthesize a plasma-like behavior in a composite. At frequencies below the plasma frequency, the real component of the effective permittivity is negative (again, due to dispersion, the dissipation attributed to the dielectric

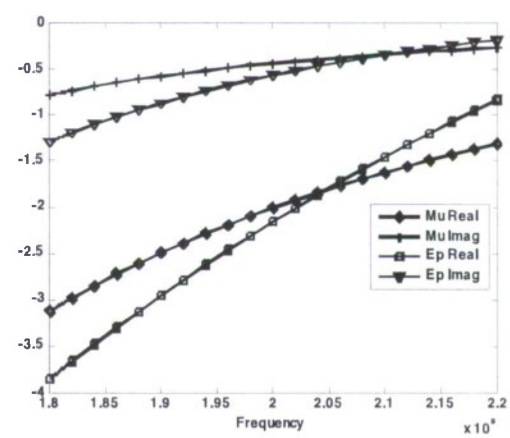


Figure 11. NIM design using alternating plasma and ferrimagnetic layers.

properties of the material is unfortunately high). Rather than approximate a plasma-like behavior, why not use a plasma! Figure 11 illustrates the effective properties of such a material in L-band (1-2GHz). This frequency range was chosen due to the properties of the ferrimagnetic material used in the design (yttrium iron garnet) and a reasonable plasma pressure in the quartz tubes. Further details can be found in [1].

SUMMARY

In this work, progress has been made in understanding the design principles for magneto-dielectric composite materials. The methods investigated are suitable for layered media and for medial comprised of rods of inclusions within a polymer matrix. These methods permit the simulation of composite materials to predict viable compositions and volume fractions to achieve desired results. Generally, it was found that layered designs resulted in a higher effective permeability relative to rods. Note that in both cases, the material is anisotropic due to the structure of the inhomogeneity. This will impact design of RF components since such anisotropy must be considered in the design due to the fact that anisotropic materials "look" different to different orientations of the dynamic electric and magnetic fields. The finite element method is well suited for analyzing anisotropic materials; however, it is noted that the wave matrix-based simulation developed by Dan Killips [1] also accounts for anisotropy.

Secondly, measurement techniques were developed for assessment of magneto-dielectric materials. This includes non-invasive, contact measurement techniques developed by Bogle [2] and Dester [14] as well as more traditional waveguide (e.g. geometrically prescriptive) methods developed by Barba [15]. These methods are important since measurement fixtures and inversion techniques are generally not well developed for magneto-dielectric materials.

Thirdly, the radiation performance of candidate magneto-dielectric materials was evaluated using full-wave, rigorous computational electromagnetics computer programs. Collaborating colleagues supported in various ways by AFOSR provided these materials. A significant conclusion is that the enhanced bandwidth realized by the most promising of these materials is attributed to loss mechanisms rather than inherent design features. This indicates that significant work on synthesis methods is still needed.

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Researchers Supported

1. Dr. Leo C. Kempel: Professor
2. Dr. Andrew Bogle: Ph. D, 2007 (and Visiting Assistant Professor)
3. Dr. Pedro Barba: Ph.D, 2006 (and Visiting Assistant Professor)
4. Dr. Dan Killips: Ph. D, 2007
5. Ozgur Tuncer: Ph.D. student.
6. Gary Dester: PhD. 2008

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